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LIQUID HYDROGEN MASS FLOWMETER

EVALUATION AND DEVELOPMENT

RKT 3658 (2)

WYLE LABORATORIES

EL SEGUNDO, CALIFORNIA

PROGRESS REPORT NO. 2

CONTRACT NO. NAS 8-1526

MARCH 31, 1961 THROUGH SEPTEMBER 30, 1961

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

REDSTONE ARSENAL

HUNTSVILLE, ALABAMA

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ABSTRACT

This report encompasses the progress achieved under Contract NAS8-1526 during the report period March 31, 1961 through September 30, 1961. Contract NAS8-1526 authorizes Wyle Laboratories to "study, modify or develop, test and evaluate a high accuracy mass flowmeter for use with liquid hydrogen" and consists of the following program phases:

1) Literature and Industry Survey

2) Analysis of "State-of-the-Art" and Selection of Most Promising Design

3) Design and Fabrication of Calibration System

4) Experimental Program

5) Analysis and Design Improvements of Flowmeter Design

Progress Report No. 1 for the period February 10 through March 31, 1961 encompassed the preliminary results of the Literature and Industry Survey. Progress Report No. 2 summarizes the results of Phases 1 and 2, includes a detailed discussion of the design philosophy of the calibration system as outlined in Phase 3, and outlines the proposed experimental program.

Technical supervision of the contract for the George C. Marshall Space Flight Center is provided by Mr. A. E. Schuler, Instrument Development Section, Measuring Control and Instrumentation Branch, Test Division.

This report has been reviewed and approved for Wyle Laboratories

L. N. Mortenson
Program Manager

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES - Cont'd

SUMMARY

In the performance of the Literature and Industry Survey, nineteen flowmeter manufacturers and seven institutions and companies of the Aerospace industry were contacted. The material compiled during the Literature and Industry Survey was utilized in the subsequent analysis phase and the selection of flowmeter designs to be evaluated in the current program.

The Potter Aeronautical Corporation twin turbine mass flowmeter and The Decker Corporation vibrating gyro mass flowmeter were selected for evaluation and development. A prototype model of the Decker mass flowmeter has been received for evaluation. Delivery of the Potter mass flowmeter is expected in the near future.

The calibration system design concepts have been finalized and the construction phases of the calibration system are essentially complete with preliminary tests utilizing liquid nitrogen expected shortly.

The experimental program for the evaluation of the Potter and Decker mass flowmeters has been established as consisting of the following:

a) Five point liquid nitrogen calibration

b) Sixteen point liquid hydrogen calibration

c) Variable density tests

The preliminary liquid nitrogen tests are expected to be initiated during October 1961.

Preliminary discussions have been held between George C. Marshall Space Flight Center personnel and Wyle Laboratories evaluating the possible extension of the program goals to include the evaluation of two additional mass flowmeters. The original program for the evaluation for the Potter and Decker mass flowmeters will continue pending the resolution of the possible addition of two meters to the evaluation program.

LITERATURE AND INDUSTRY SURVEY

As previously outlined in Progress Report No. 1, the survey phase of the program was conducted utilizing the Armour Research Report "Study of Mass Flowmeters" ARF Project D-173, Contract DA-11-022-ORD-2857 as the preliminary basis for contacting manufacturers and developers of mass flowmeters. In conjunction with the industry survey, the program objectives and philosophy were discussed with each manufacturer and/or government agency contacted as outlined below:

a) Program requirements for flowmeter performance.

b) Principle of flowmeter operation.

c) Potential problem areas in the use of the flowmeter in a liquid hydrogen mass flow measurement application.

d) Possible willingness of the manufacturer to participate in the evaluation phase of the program (submittal of meter on a loan basis and subsequent active participation in the data analysis and possible design improvement phases).

e) Experience in either the field of mass flow measurement or the field of cryogenic flow measurement.

f) Possible sources of additional technical information.

The detailed results of the Literature and Industry Survey which have been reported previously are summarized in the following table. (Note: A more detailed discussion of the various types of flowmeters may be found in References 1, 2 and 3).

TABLE 1

Summary of Cryogenic Mass Flowmeter Survey

Organizations Contacted	Type of Instrument
Avien, Inc.	Angular momentum. Two turbines driven in opposite directions impart angular momentum to fluid which is removed in third torque wheel. Resultant torque is proportional to mass flow rate.
The Bendix Corporation Pioneer Central Division	Angular momentum. Single turbine driven at constant speed through a linear spring. Time period between driving motor and coupled turbine proportional to mass flow.
Consolidated Electrodynamics Corporation	Heat transfer (boundary layer).
Cox Division George L. Nankervis Co.	Turbine volume meter with density compensation.
Daniel Orifice Fitting Co.	Head meter with velocity compensation.
The Decker Corporation	Vibrating Gyro.
Fischer & Porter Co.	Turbine volume meter with flow momentum drag body.
Flow Measurement Corporation	Heat transfer (boundary layer) Two basic types: a) Constant heat input; temperature rise related to mass flow. b) Constant temperature rise; heat input related to mass flow.
Francisco Engineering Co., Inc.	Turbine volume meter with density compensation.

TABLE 1 - Cont'd

Summary of Cryogenic Mass Flowmeter Survey

Organizations Contacted	Type of Instrument
General Electric Company	Angular momentum. Turbine driven at constant speed imparts angular momentum to fluid which is removed in a second turbine. Resultant torque on second turbine is proportional to mass flow rate.
Gulton Industries, Inc.	Acoustic volume meter with density compensation.
W. L. Maxson Company	Acoustic volume meter with density compensation.
Millrich Engineering Company	Head meter with variable contoured orifice. Orifice area controlled by fluid density.
Potter Aeronautical Corporation	Twin turbine with linear spring coupling. Phase angle between turbines proportional to flow momentum with time period between rotating turbines proportional to mass flow.
Quantomics Company	Turbine volume meter with density compensation.
Revere Corporation of American	Turbine volume meter with density compensation.

TABLE 1 - Cont'd

Summary of Cryogenic Mass Flowmeter Survey

Organizations Contacted	Type of Instrument
Space Instrumentation Corp	Twin turbine type with servo drive.
Standard Controls, Inc.	Drag on flexible reed. Flow momentum instrument with limited density compensation due to variable area.
Waugh Engineering Company	Angular momentum. Single turbine driven with constant torque motor, turbine speed inversely proportional to mass flow.

ANALYSIS OF "STATE-OF-THE-ART" & SELECTION OF MOST PROMISING DESIGN

In reviewing the current "State-of-the-Art" of the flowmeter industry and in attempting to select the most promising cryogenic mass flowmeter design for subsequent evaluation in the experimental portion of the program, several restraints were established:

1) Since a complete experimental evaluation of all available mass flowmeters was impractical, a limit of two flowmeter designs was arbitrarily established as the maximum number to be evaluated during the current program.

2) Emphasis was placed upon the evaluation of the true mass flowmeters rather than inferential type instruments combining various volume and density signals external to the meter for the prediction of the mass flow rate.

3) The program goals for the development of a mass flowmeter principle were tentatively established as

    a. Capable of measuring either single or two phase flow.

    b. Flow range: 30 to 300 pounds per minute of liquid hydrogen.

    c. Accuracy: better than ± 0.5%.

4) For the current program, evaluation and development of meter designs was limited to reasonably well developed instruments. Additional restraints were imposed which required that the instrument manufacturer be willing to submit a flowmeter on a loan basis for evaluation and participate in the data analysis and possible design improvement phases.

5) The selection was further limited to meter designs with some existing experimental data substantiating a reasonable expectation of attaining an accuracy of ± 0.5%.

Within the confines of the above restrictions, the Potter twin turbine mass flowmeter and the Decker Corporation vibrating gyro mass flowmeter were selected for evaluation and development during the current program. The Potter twin turbine mass flowmeter and the Decker Corporation vibrating gyro mass flowmeter are more fully described in subsequent sections.

Potter Twin Turbine Mass Flowmeter

The Potter mass flowmeter design is based upon established principles of volumetric turbine flowmeter design with a unique adaptation to provide mass flow information. The mass flowmeter, as shown in Figure 1, consists of two rotor assemblies coupled through a linear torsion member. A difference in blade angle between the two rotor assemblies would normally cause the assemblies to rotate at slightly different velocities; however, due to the linear torsion member, the two rotor assemblies are forced to rotate at an average velocity. The torsional restraint of the torsion may be shown to be proportional to the mass flow momentum; thus, the phase angle between the forward and rear rotor assemblies may be shown to be proportional to mass flow momentum. Since the velocity of the coupled rotors is proportional to volume of flow, the period between the passing of a fixed reference point on the forward rotor assembly and a fixed reference point on the rear rotor assembly is proportional to mass flow.

The advantages of the Potter mass flowmeter system may be briefly summarized as follows:

1) The flowmeter design is relatively simple and is passive in nature.

2) Experimental results with both water and liquid oxygen indicate an expected performance within ± 0.5%.

3) Provides both digital volume information and digital mass flow information.

The Potter mass flowmeter system possesses several characteristics, as outlined below, which might be considered undesirable in certin applications:

1) The rotor assembly, in the present configuration, may be subject to overspeeding during cooldown phases in cryogenic applications.

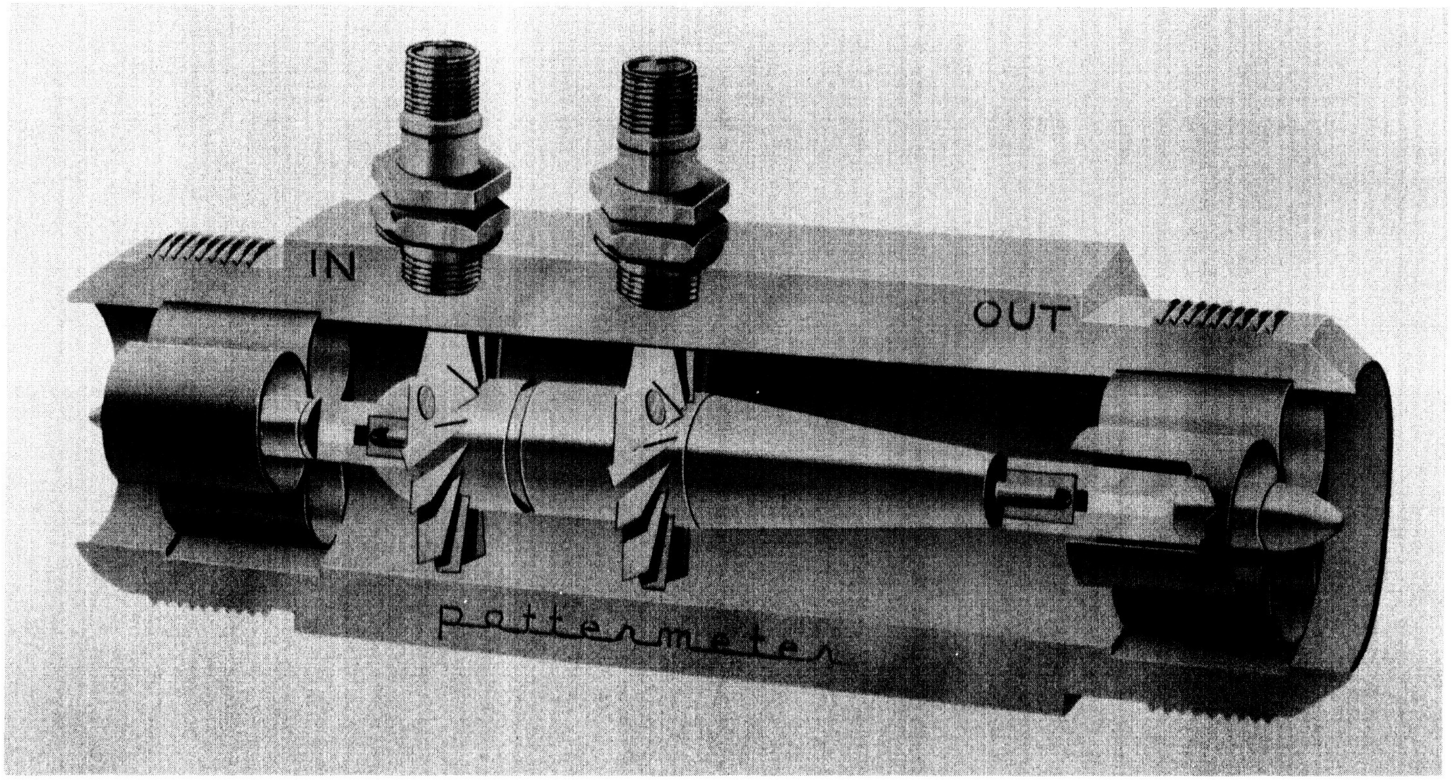

FIGURE 1

POTTER TWIN TURBINE MASS FLOWMETER

2) The flow range is limited by the displacement angle between the two rotors which is proportional to the mass flow momentum.

3) Accurate determination of the time period between the two rotor assemblies may be difficult in some applications.

4) Through the use of two rotating assemblies, coupled with a torsion member, undesirable oscillations may be encountered between the two rotor assemblies.

<u>The Decker Corporation Vibrating Gyro Mass Flowmeter</u>

The Decker mass flowmeter is based upon the classical principle of the gyroscope in which the flowing liquid is caused to transverse a circular path simulating the rotating flywheel of the gyroscope. The circular loop of the flowing liquid is forced to precess in an oscillating manner through the use of a mechanical vibration link. As a result of the forced precession, an orthogonal torque is produced in the flow loop which is also sinusoidal in nature. The resultant torque is restrained by linear torsion members, with the resultant displacement in the orthogonal plane a linear measure of the mass flow rate. The Decker mass flowmeter which will be evaluated in the current program is shown in Figure 2.

Attractive features of the Decker mass flowmeter may be briefly summarized as follows:

1) Experimental results obtained by The Decker Corporation, indicate performance to within $\pm$ 0.5% using water as the test medium over an extreme flow range.

2) Absence of internal obstructions or rotating assemblies in the fluid stream.

The Decker mass flowmeter system possesses several characteristics, as outlined below, which might be considered undesirable in certain applications:

1) Basic output signal from the meter is 0 to 50 mv, which is subsequently digitized in an analog to digital conversion circuit for totalizing.

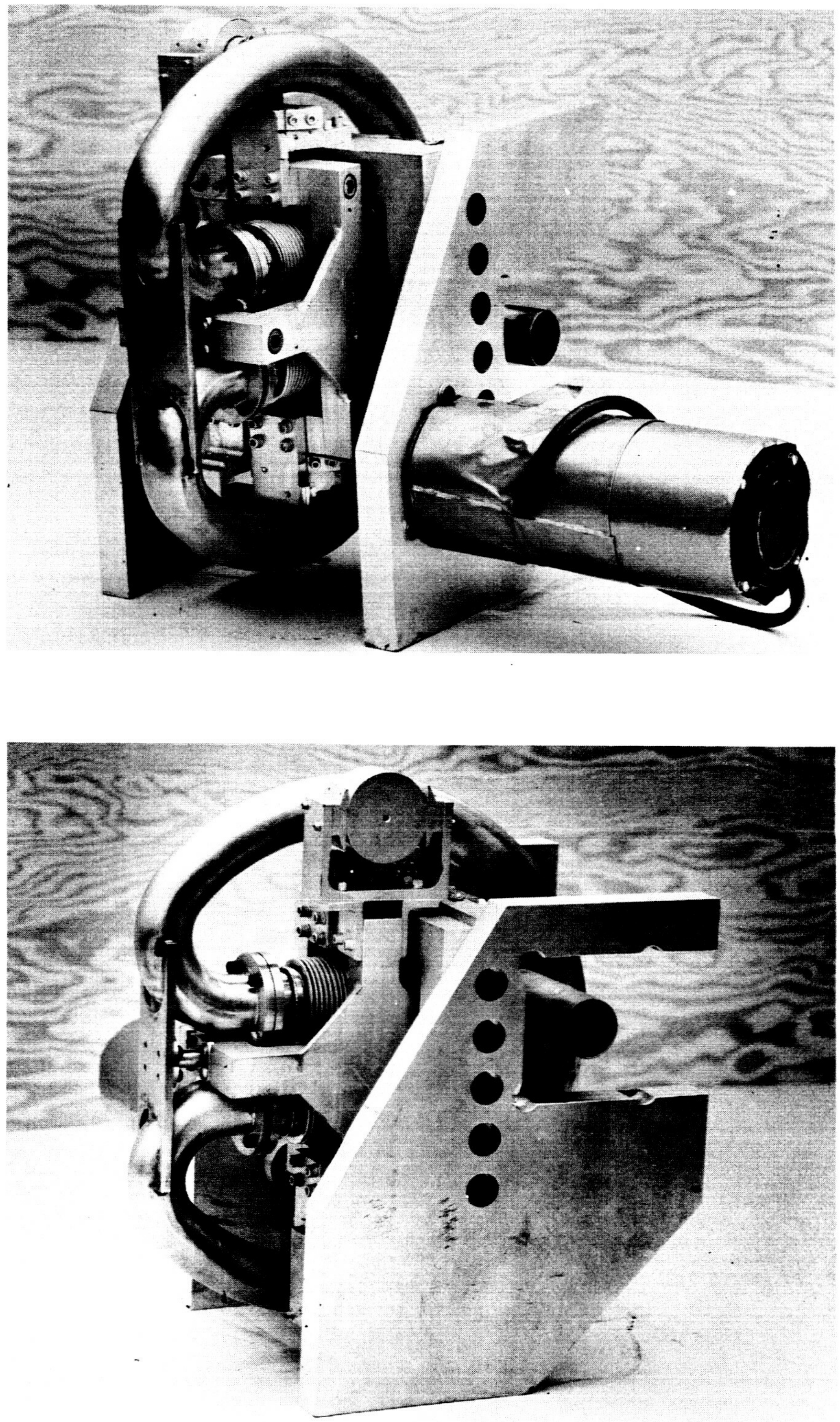

FIGURE 2

THE DECKER CORPORATION VIBRATING GYRO MASS FLOWMETER

2) Large, bulky physical configuration which is unsuitable for flight applications.

3) Requires the use of a motor-drive assembly.

4) Due to a complex flow path, the meter possesses a rather high head loss.

DESIGN AND FABRICATION OF CALIBRATION SYSTEM

General

The experimental portion of the flowmeter development program will be conducted at the Wyle Laboratories Norco Test Facility. The Norco Facility consists of approximately 500 acres developed for the performance of hazardous tests with liquid oxygen, liquid hydrogen, storable propellants and solid propellants. Figure 3 depicts the general location of each test complex.

The liquid hydrogen facility consists of a 13,000-gallon vacuum-jacketed hydrogen storage vessel, a 30 x 40 foot slab area, a 20 x 40 foot remote control block house and work area and supporting liquid nitrogen and helium pressurization systems.

Discussion of Calibration Techniques

In designing a flowmeter calibration system, two basic techniques are available; the time-volume technique and the time-weight technique. It is perhaps noteworthy at this time to briefly summarize the relative advantages and disadvantages of the two calibration techniques.

Time-Volume Calibration System

The time-volume technique is based upon either the continuous or discrete measurement of volume versus time. In general, the discrete method is considered capable of providing better accuracy than the continuous techniques, and, as such, the subsequent discussions will be limited to discrete methods.

Discrete volume measurements are usually made using point level sensors. Level sensors are installed in the calibration tank and the volume between the level sensors is precisely determined. An initial volume, V_1, is usually provided prior to the actuation of the upper level switch, S_1. This initial volume provides for the establishment of stable flow prior to the actuation of switch S_1. The flow rate during the expulsion of the calibrated volume between the upper and lower switches, is maintained constant. As the liquid level reaches the lower level switch, S_2, a second timing pulse is generated. The totalized flowmeter output signal during the time period between level switch actuations S_1 and S_2, is then compared with the volume between the level switches S_1 and S_2. The flow rate is obtained by dividing the total volume between switch S_1 and S_2 by the elapsed time between switch actuations.

FIGURE 3

WYLE LABORATORIES NORCO TEST FACILITY

Pertinent aspects of the time-volume calibration system may be briefly summarized as follows:

1) Requires the use of a specially designed tank to optimize height versus volume conditions.

2) Ideally suited for the calibration of volume flowmeters since the volume between switch S_1 and S_2 is compared with the totalized volume signal obtained directly from the flowmeter being calibrated.

3) Requires a density conversion for the calibration of a mass flowmeter.

4) Requires prudent selection of level switches and design of the level switch installation.

5) Obtaining the correct volume between switch S_1 and S_2 for use in cryogenic application may be difficult since the volume, as calibrated with water, must then be corrected using analytical techniques to obtain the contracted volume at cryogenic conditions. An alternate approach for calibrating the volume between switch S_1 and S_2 is to weigh the tank plus contents with the actual cryogenic fluid in the tank. The weight change between switches S_1 and S_2 is then converted to the volume of cryogenic fluid using the temperature density characteristics of the fluid.

6) Unaffected by extraneous environments such as side loading, wind, piping connections, etc.

7) As noted in Reference 10, the calibration of cryogenic flowmeters must be conducted in a closed system to properly account for possible boil-off losses. The time-volume technique may be adapted to either closed system or open system operation.

Time-Weight Calibration System

The time-weight technique is based upon either the continuous or discrete measurement of weight change versus time. Weight measurements are usually made using either strain gauge techniques or beam balance-type scales. In general, the discrete method is considered capable of providing better accuracy than the continuous techniques, and, as such, the subsequent discussions will be limited to discrete methods.

In the discrete weight change method, an initial weight of fluid is usually provided prior to the initial balance point B_1. This initial weight is provided for the establishment of stable flow, prior to the initial balance condition. The flow rate during the expulsion ot the calibrated weight between the initial and final balance conditions is maintained constant. The weight of fluid during the calibration period between beam balance conditions B_1 and B_2 may be simulated by either the removal of counter poise weights from the balance arm, or the actual addition of a calibrated weight to the scale platform. As the second balance position is approached, a final timing pulse is generated. The totalized flowmeter output signal during the time period between initial and final scale balance positions B_1 and B_2 is then compared with the weight of fluid expelled from the calibration tank during the calibration period. In the calibration of volume type instruments, the basic weight change of the scale must be converted to a corresponding volume, by means of the temperature-density characteristics of the calibration fluid.

Pertinent aspects of the time-weight calibration system may be briefly summarized as follows:

1) Requires the use of specially designed lightweight tank configurations, or special techniques in the weighing system to eliminate a large system deadweight.

2) Ideally suited for the calibration of mass flowmeters, since the weight change between scale balance points B_1 and B_2 is compared with the totalized mass signal obtained directly from the flowmeter being calibrated.

3) Requires a density conversion for calibration of volume flowmeters.

4) Requires prudent selection of the weighing system and weighing system installation.

5) The calibration tank pressurization medium added to the weighing system during the calibration period must be metered.

6) The system installation must be carefully designed to eliminate or minimize extraneous loading of the weighing system; i.e., side thrust loading, wind loading, piping connections, etc.

7) As noted in Reference 10, the calibration of cryogenic flowmeters must be conducted in a closed system to properly account for possible boil-off losses. The time-weight techniques can be adapted to either closed system or open system operation.

Calibration System

The time-weight calibration technique was selected for the present program. This selection was based primarily on previous experience of Wyle with the design and operation of time-weight calibration systems and the distinct advantage of obtaining a basic weight measurement in the calibration of mass flowmeters; thus, eliminating the necessity of highly precise temperature measurements and subsequent density conversions.

The calibration system, as shown in Figure 4 through Figure 8 consists of a 650-gallon calibration tank mounted upon a beam balance platform scale. Fluid flow from the calibration tank is achieved by pressurization of the calibration tank with helium. To eliminate the necessity of metering the quantity of helium pressurization gas during a calibration run, a self-contained helium pressurization system is mounted upon the scale platform. Connecting lines between the system mounted upon the platform scale and external ground reference have been held to an absolute minimum. The largest connection between the scale system and ground reference is a 3-inch vacuum-jacketed flex hose through which the fluid is withdrawn from the calibration tank.

As indicated in Figure 4, fluid leaving the scale system enters a vacuum-jacketed transfer system, subsequently being returned to the 13,000-gallon recovery vessel. The vacuum-jacketed transfer system is specially designed and fabricated as shown in Figures 9 and 10 to include a removable vacuum shell from a section of line approximately ten feet long. The technique of utilizing a removable vacuum shell facilitates the installation of the flowmeter undergoing calibration and additional instrumentation. All instrumentation is contained within the removable vacuum shell section.

In addition to the individual instrumentation requirements of the flowmeter undergoing calibration, instrumentation of the following nature will be installed in the test section:

1) Several temperature measuring devices such as thermocouple probes, resistance temperature bulbs and solid state temperature devices.

2) A specially designed low blade angle volume flowmeter.

3) A Venturi meter as shown in Figure 11.

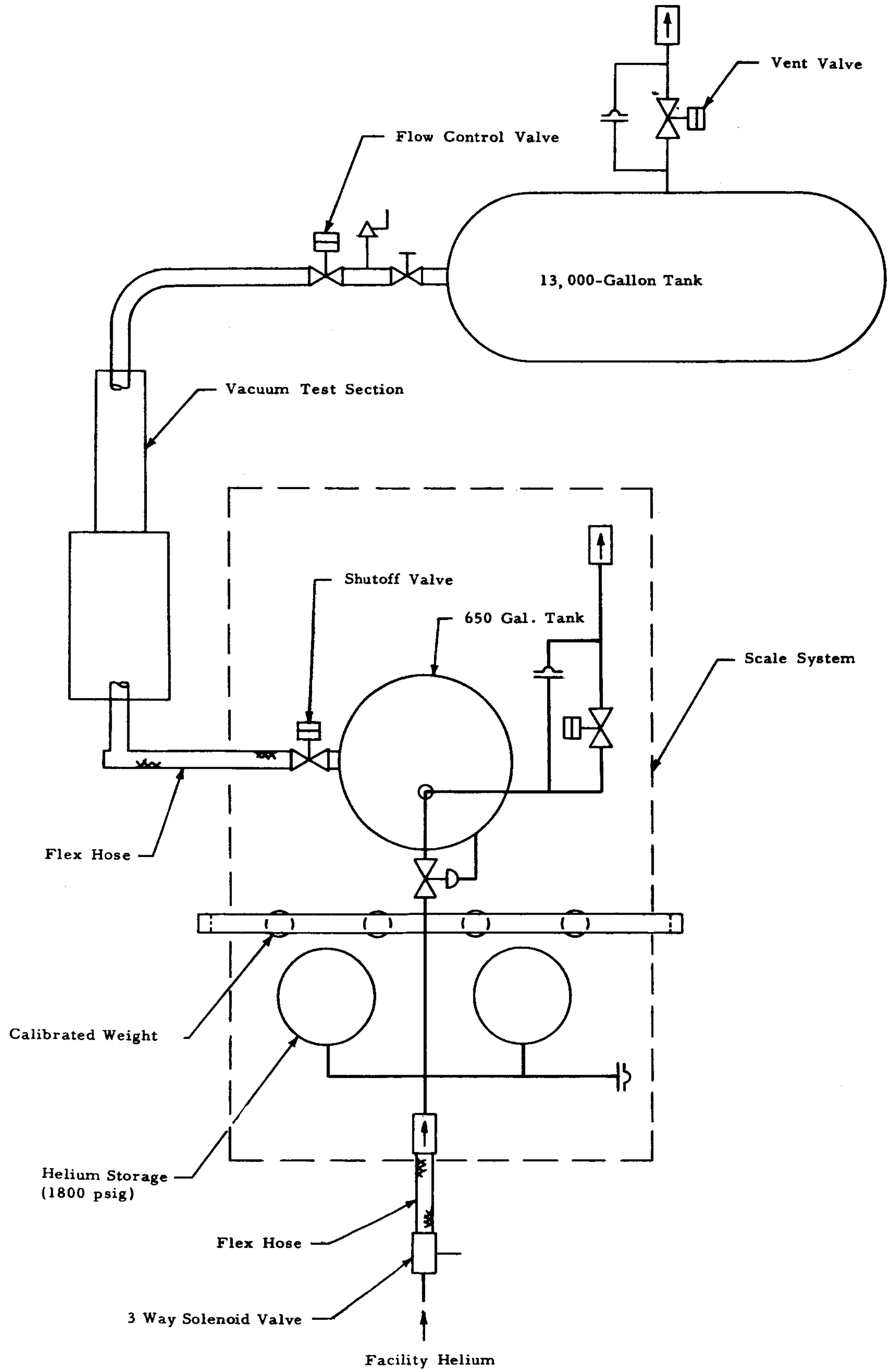

FIGURE 4

SCHEMATIC OF TIME-WEIGHT FLOWMETER CALIBRATION TEST SYSTEM

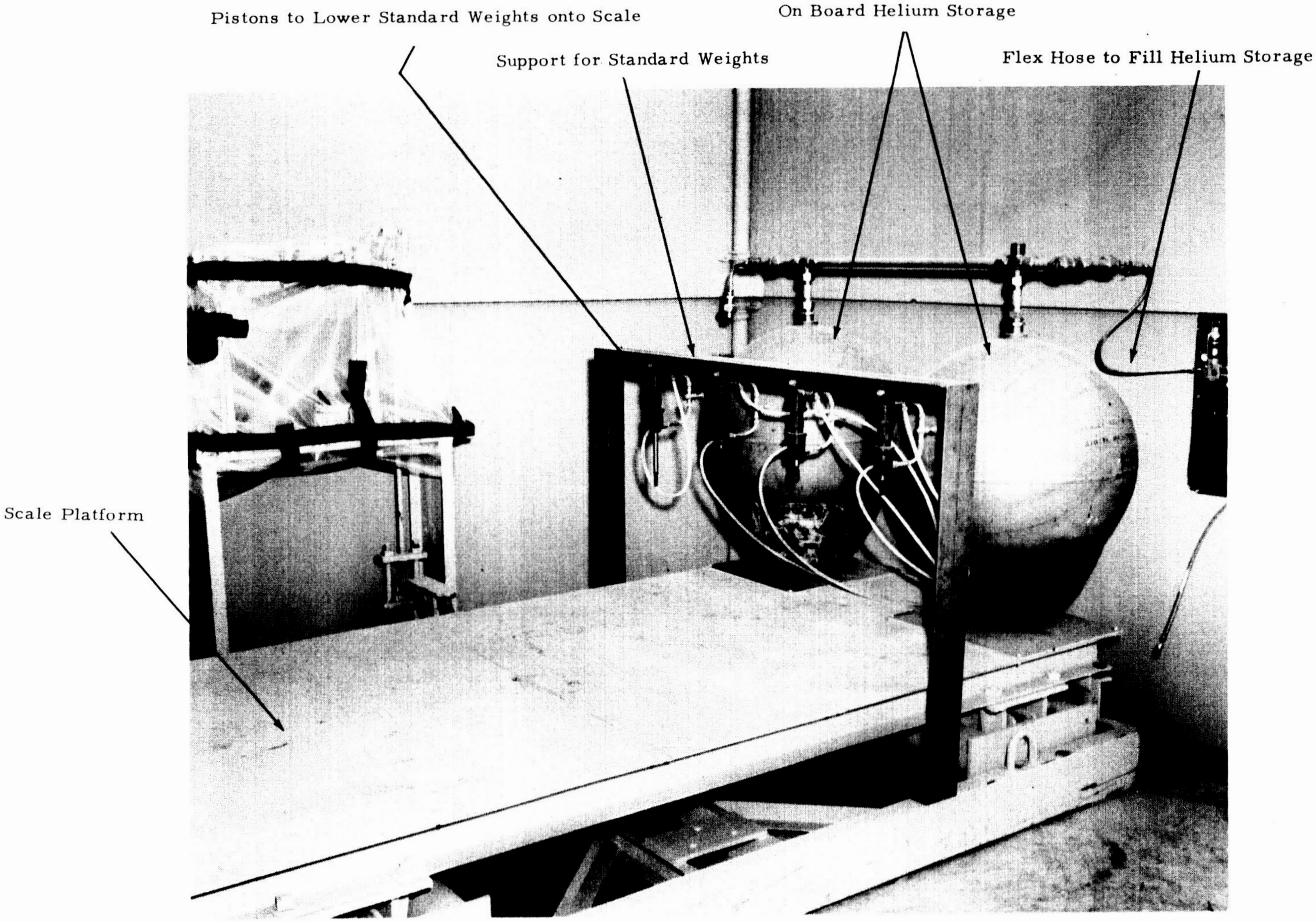

FIGURE 5

SCALE PLATFORM INSTALLATION

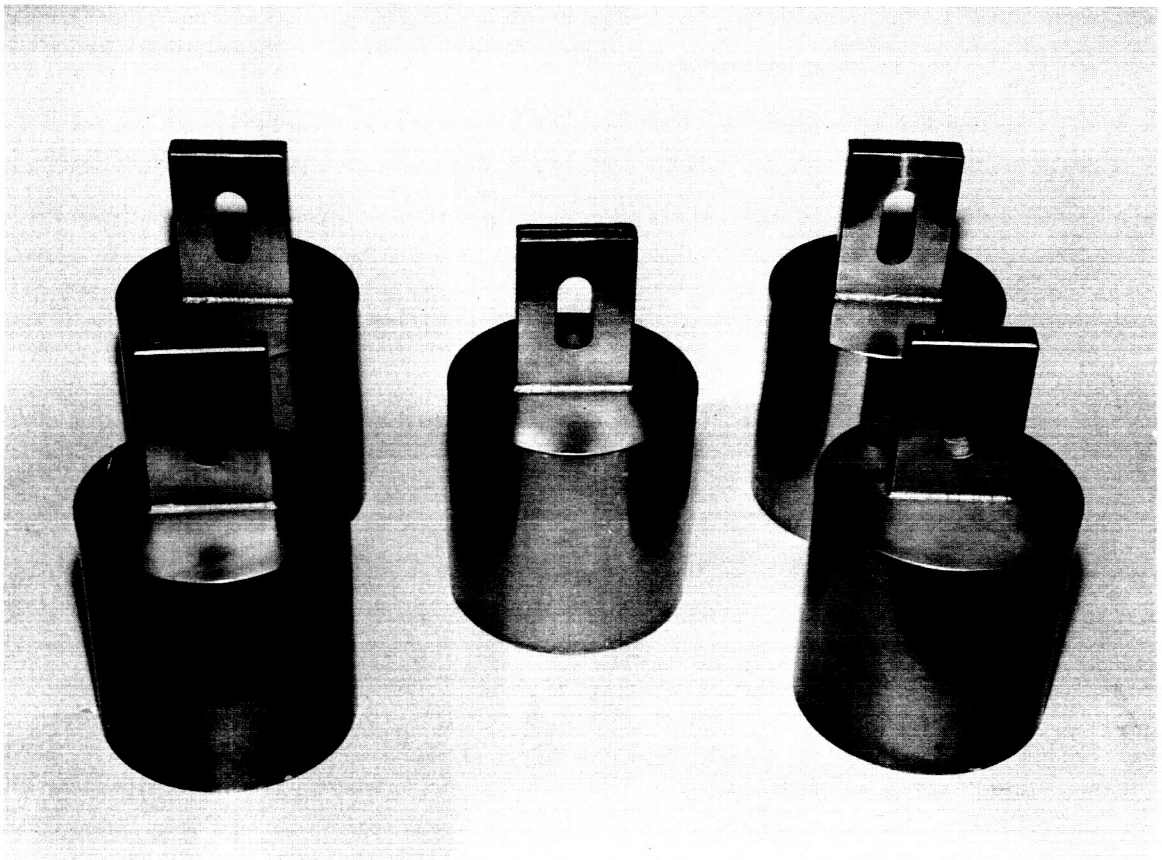

FIGURE 6

CALIBRATED STANDARD WEIGHTS
(nominal 50-pound weights)

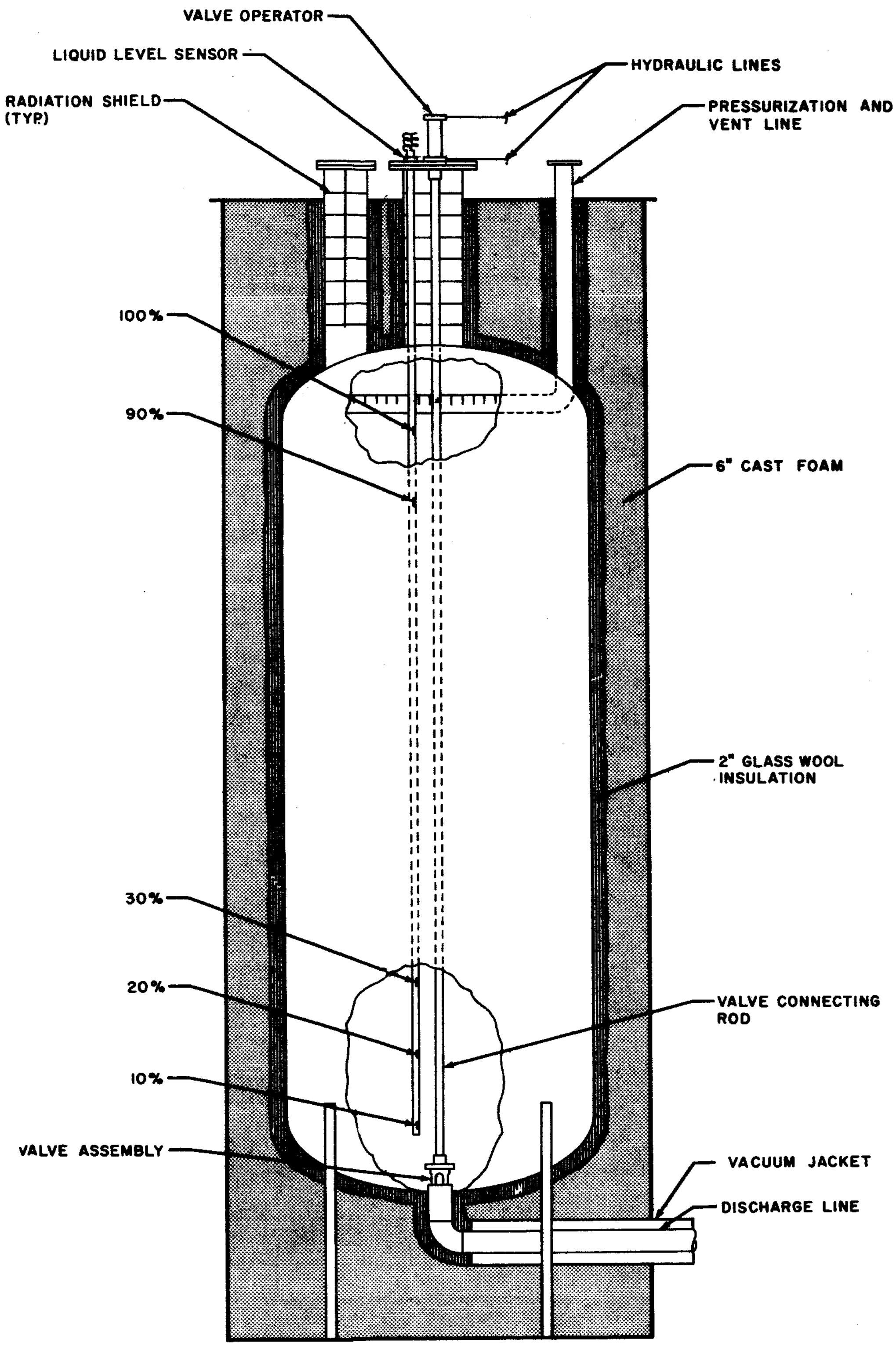

FIGURE 7

SCHEMATIC OF 650-GALLON SCALE
MOUNTED CALIBRATION TANK

Liquid Nitrogen (1000 Gal.)

Helium (54 cu. ft.)

Liquid Hydrogen (13,000 Gal.)

FIGURE 8

HELIUM, NITROGEN AND HYDROGEN
STORAGE AND SUPPORT FACILITY

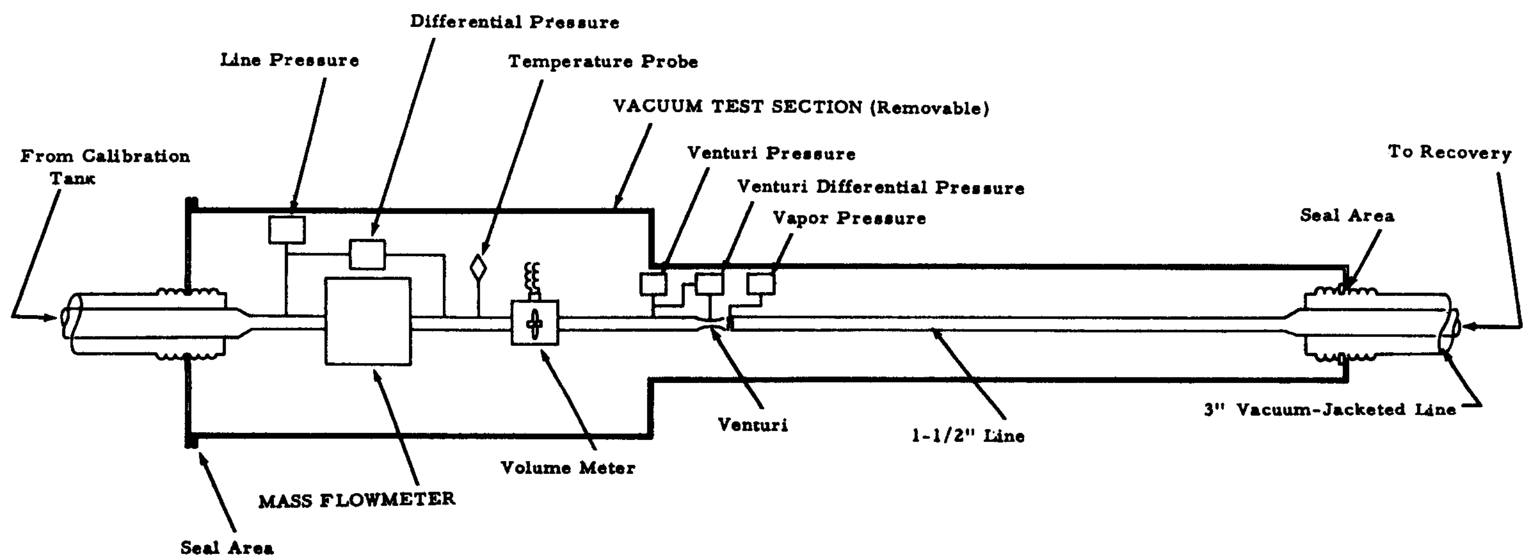

FIGURE 9

SCHEMATIC OF REMOVABLE VACUUM TEST SECTION

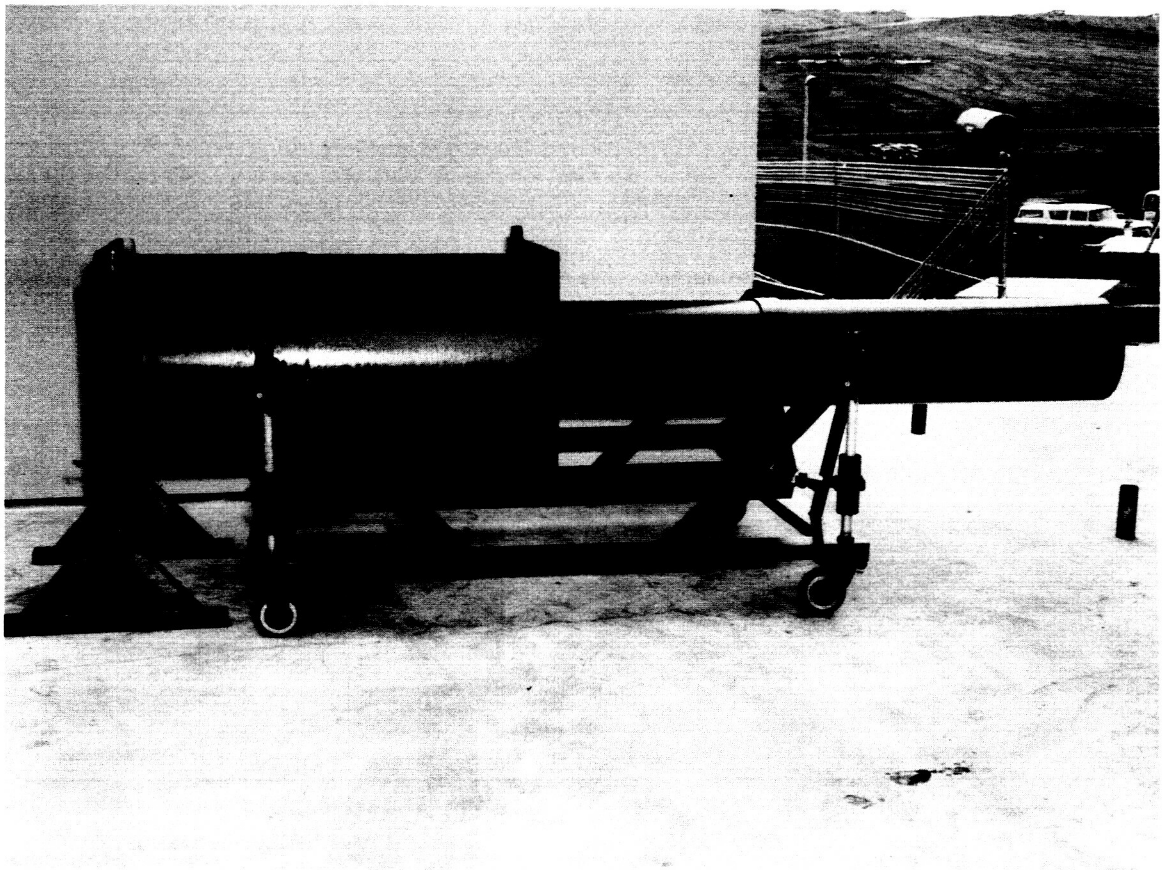

FIGURE 10

OUTER SHELL OF REMOVABLE VACUUM TEST SECTION

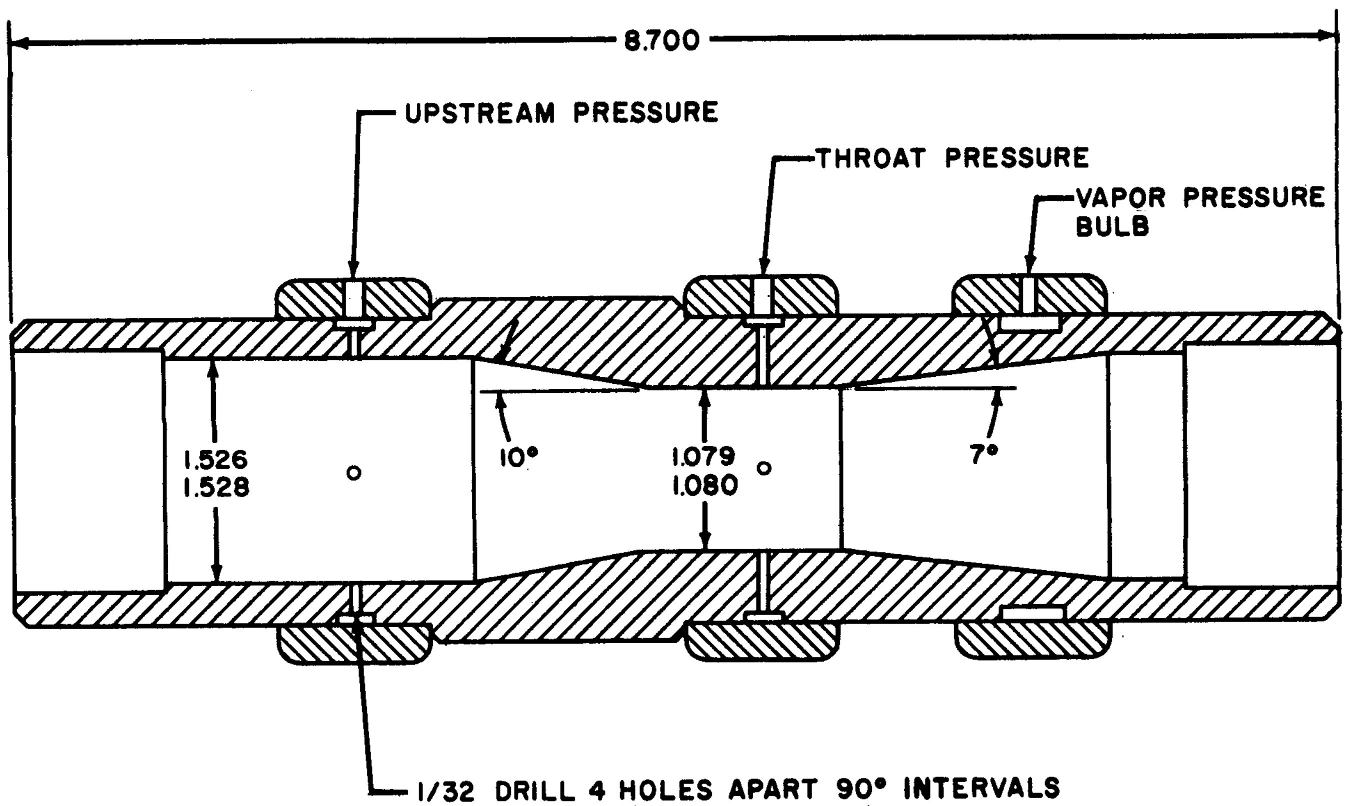

FIGURE 11

CONSTRUCTION DETAILS OF VENTURI INSTALLED
IN CALIBRATION SYSTEM

The 650-gallon calibration tank incorporates the use of an integral shut-off valve and a unique method of foamed-in-place insulation. The integral shut-off valve design is similar to a bathtub plug concept as shown in Figures 7 and 12. This approach to the use of an integral shut-off valve has several advantages over alternate concepts such as minimum heat leak, minimum weight, zero external leakage, fail-safe operation, capable of utilizing high seat loading forces in conjunction with the easily renewable soft seat, and full ported low pressure drop design. The concept of tank insulation is one in which the inner stainless steel vessel is wrapped with approximately two inch thick glass-type insulation prior to casting the foam insulation. The mold for the foam insulation is also the permanent outer shell of the completed tank assembly. The outer shell design is such that it may be completely sealed and rendered impervious to vapor transmission. The concepts of using a collapsible spacer material between the plastic foam and the inner tank and the vapor-type outer shell are felt to be quite promising in the attainment of a light economic storage vessel which may be used for long term applications without the normally attendant problems which confront users of cast-in-place foam insulations such as cracking, deterioration of the plastic foam due to atmospheric conditions and water vapor diffusion into the plastic foam.

In addition to the basic gravimetric design, provisions were incorporated into the design of the 650-gallon calibration tank to include the installation of liquid level sensors; thus allowing the possibility of utilizing time-volume calibration techniques to substantiate the time-weight calibration data. In support of this effort, the 650-gallon tank was designed with an additional 6-inch access port and was designed to provide height-volume characteristics suitable for adaptation in a time-volume calibration system. The tank has been calibrated several times with water. The resultant height versus volume characteristics are shown in Figures 15 and 16. If level sensors are installed at a later date to provide time-volume calibration data, an additional calibration of the tank will be conducted with the actual cryogenic fluid to determine the volume of fluid between the level sensors in their installed positions under the actual cryogenic conditions to be encountered.

Calibration Procedure

The calibration of a flowmeter is performed in a point-to-point manner; i.e., to obtain a single calibration point, one complete test run is required since the totalized output of the flowmeter is compared with the total weight change on the scale system. Following the installation of the flowmeter in the test section, a typical test run is conducted in the following manner:

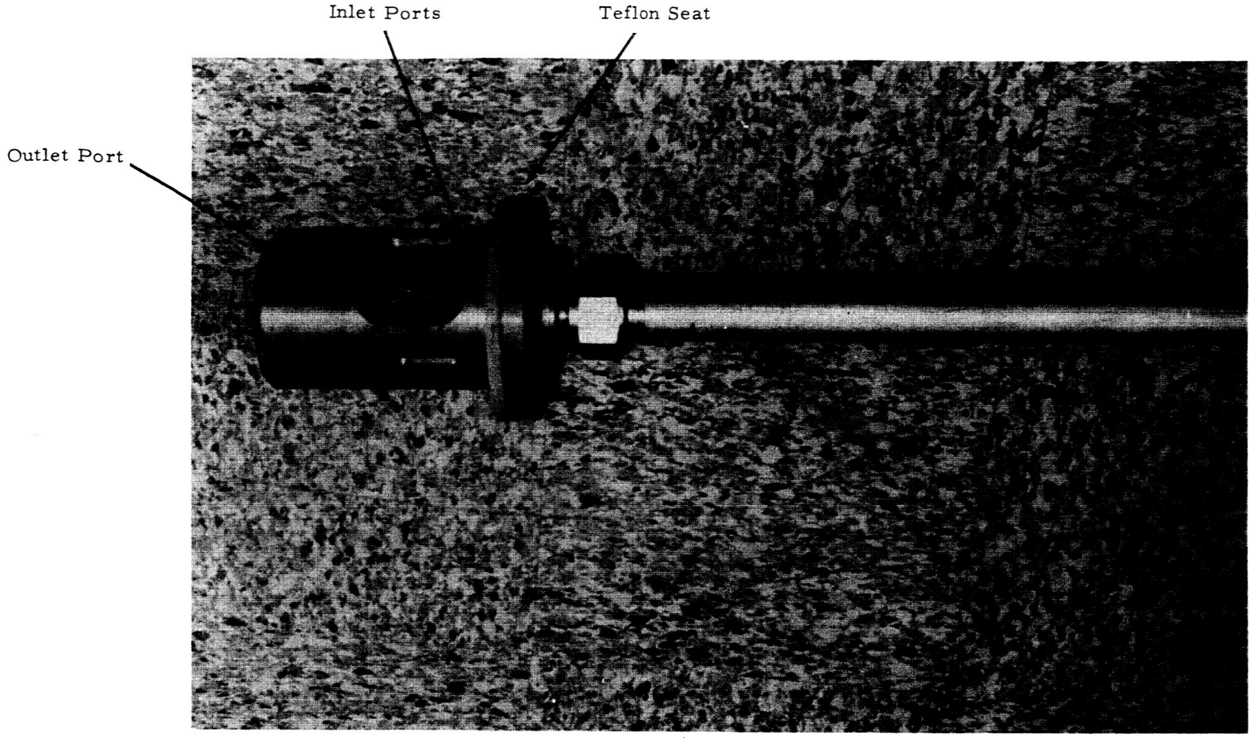

FIGURE 12

CONSTRUCTION DETAILS PLUG VALVE USED IN 650-GALLON CALIBRATION TANK

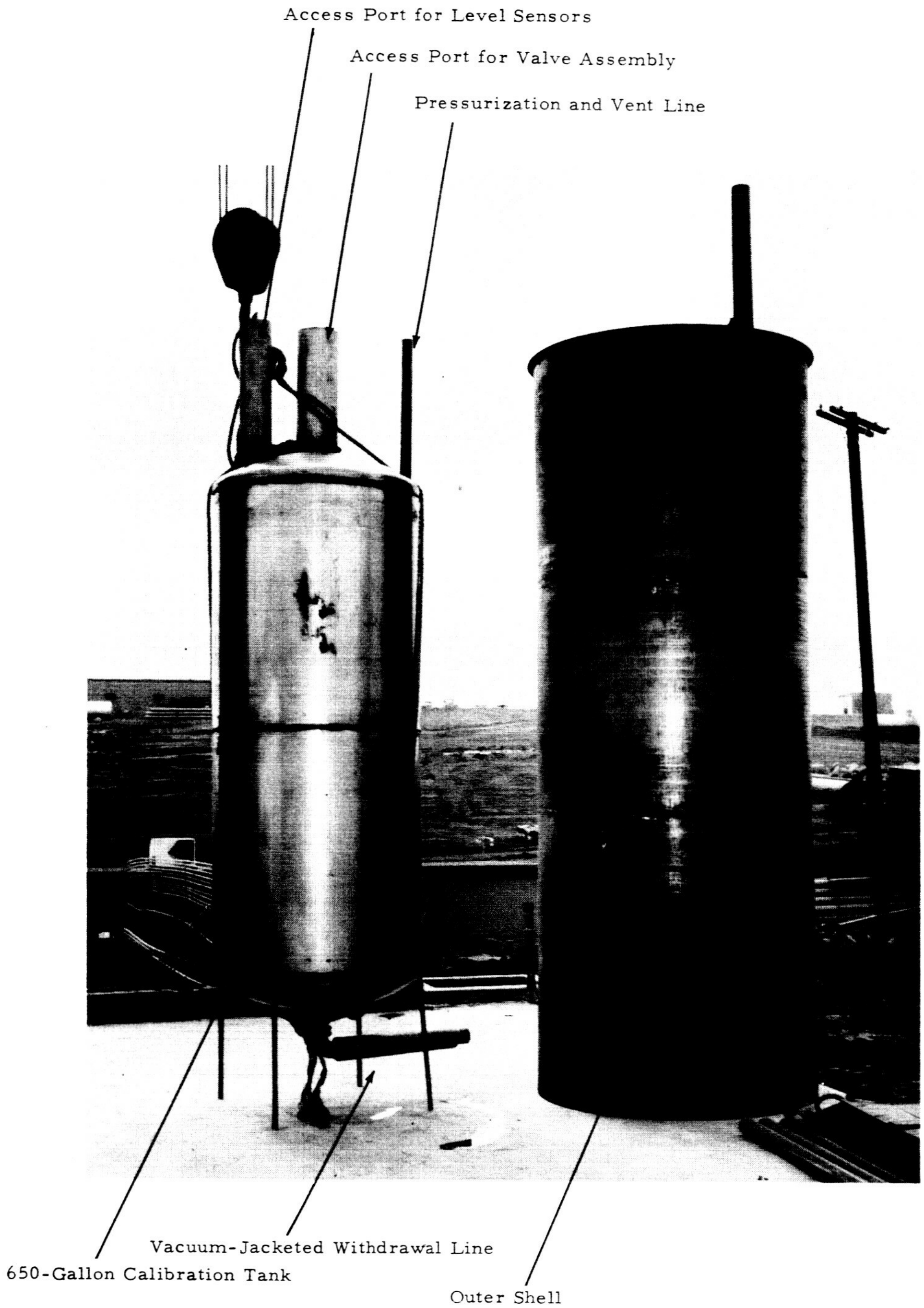

FIGURE 13

INNER AND OUTER SHELL ASSEMBLIES OF 650-GALLON CALIBRATION TANK PRIOR TO APPLICATION OF FIBERGLASS AND CAST FOAM INSULATION

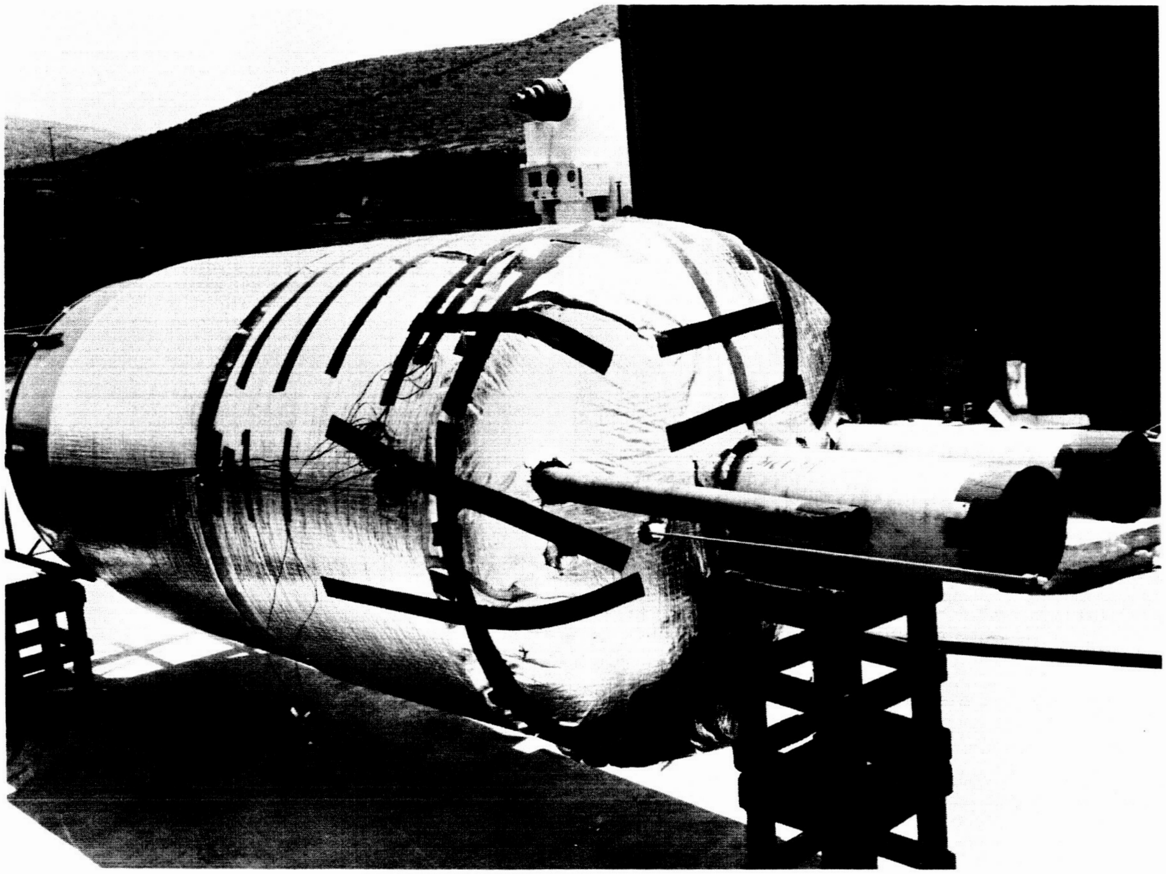

FIGURE 14

INNER VESSEL OF 650-GALLON CALIBRATION TANK DURING APPLICATION OF FIBERGLASS PRIOR TO APPLICATION OF CAST FOAM INSULATION

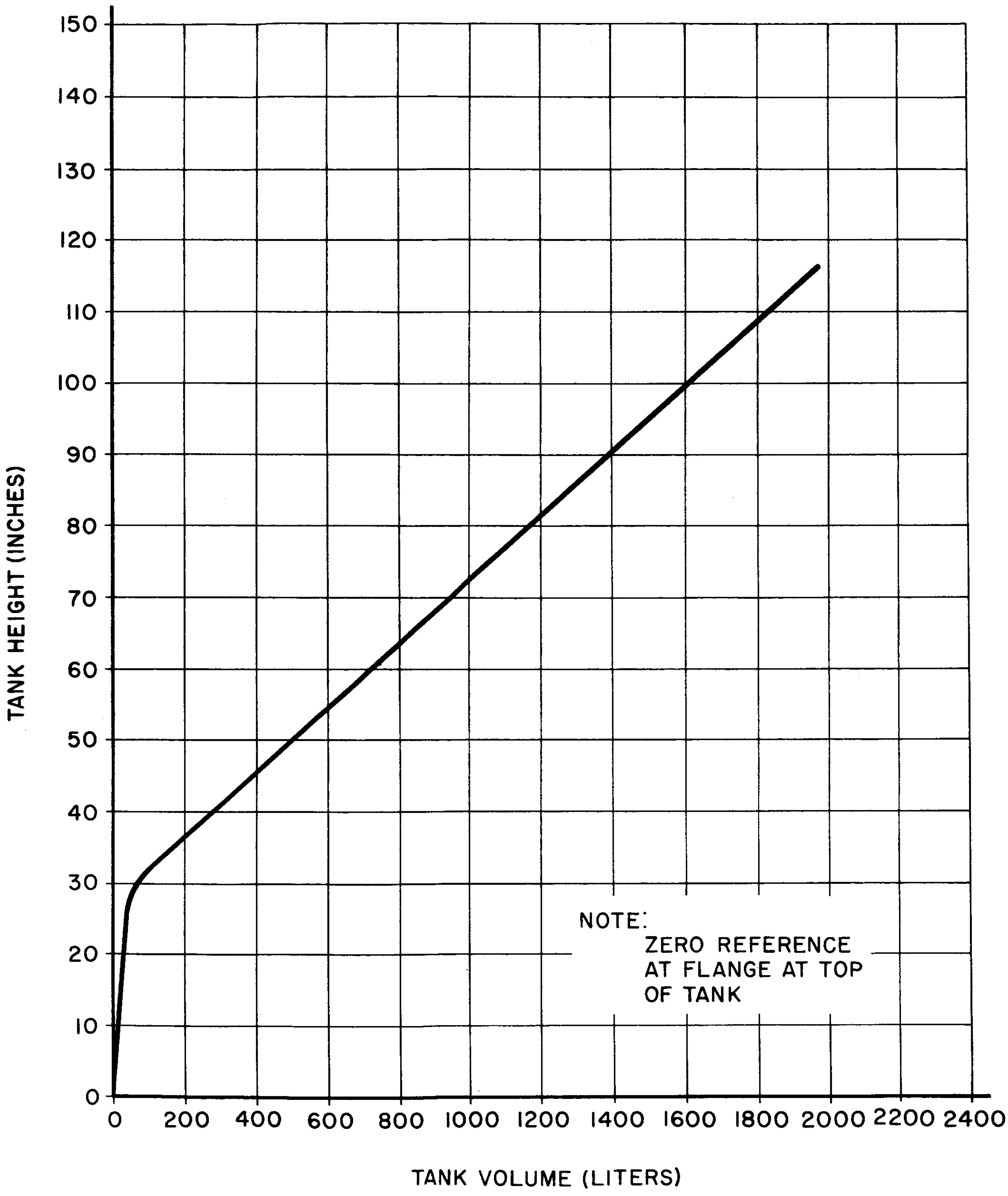

FIGURE 15

VOLUMETRIC CALIBRATION OF 650-GALLON
CALIBRATION TANK

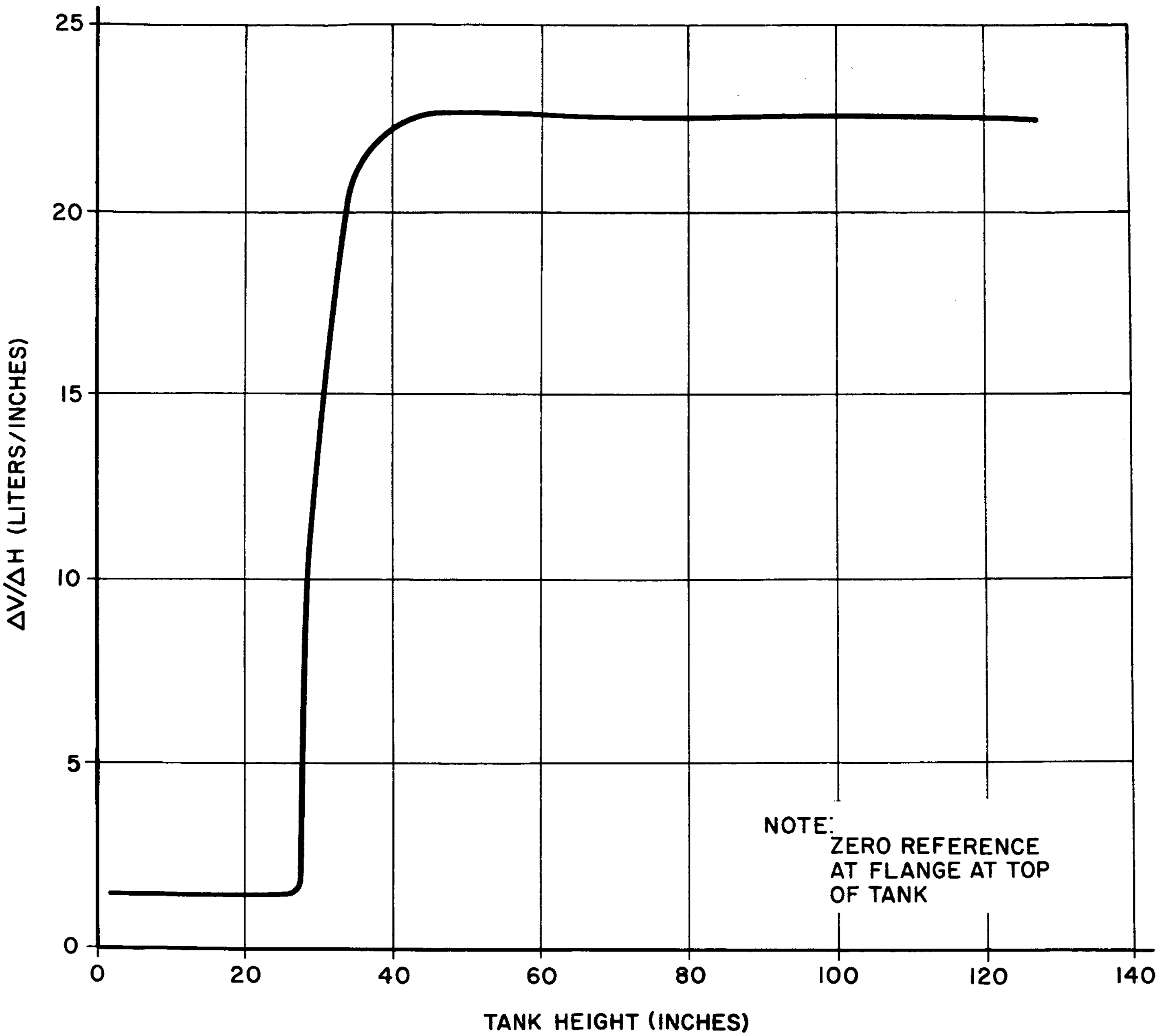

FIGURE 16

VOLUMETRIC CALIBRATION OF 650-GALLON
CALIBRATION TANK

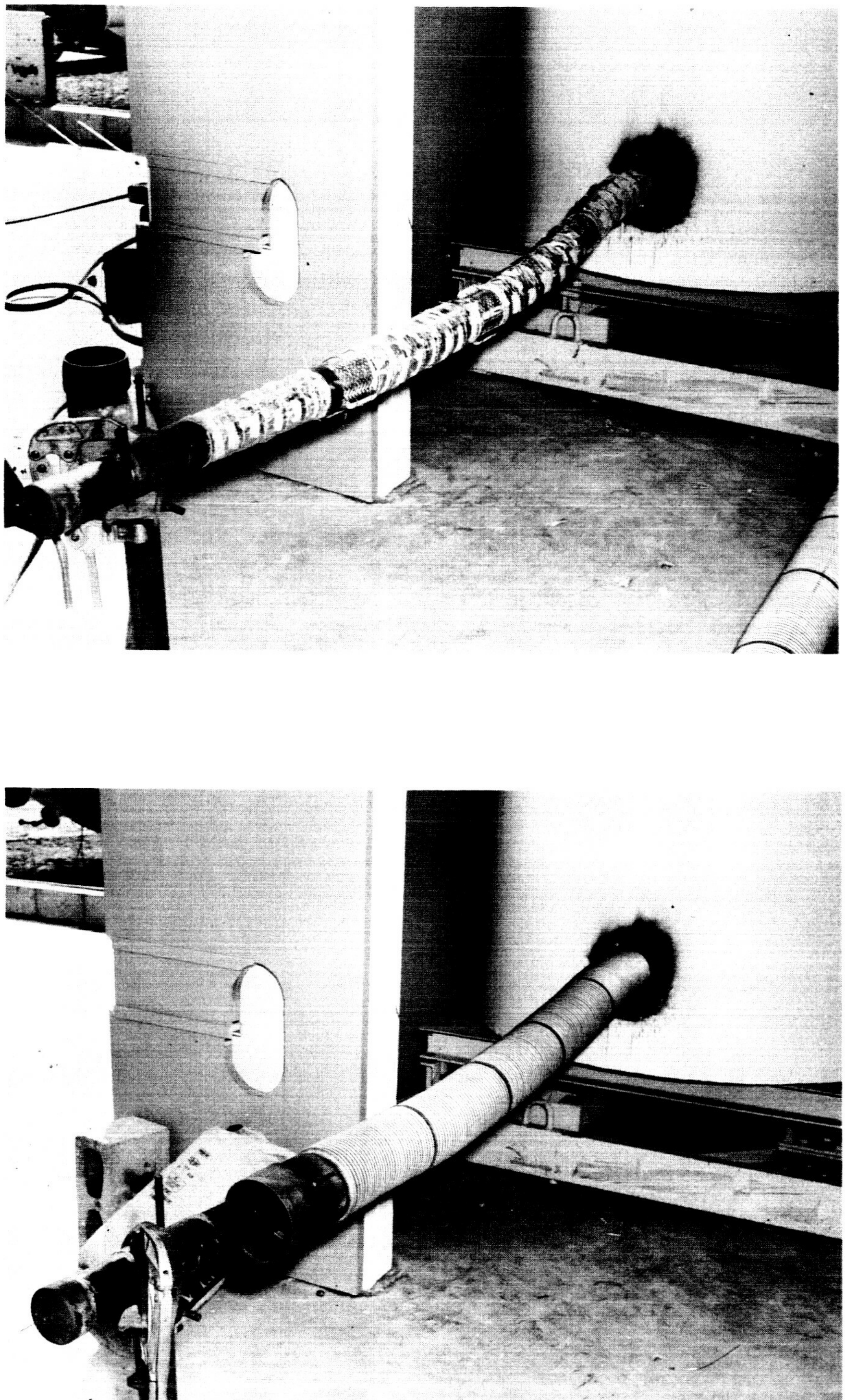

FIGURE 17

CONSTRUCTION DETAILS OF VACUUM-JACKETED FLEX HOSE BETWEEN 650-GALLON CALIBRATION TANK AND TEST SYSTEM

The test fluid is introduced into the 3-inch vacuum-jacketed line and allowed to backflow through the flowmeter into the vented 650-gallon calibration tank. During the filling of the 650-gallon calibration tank, the test fluid is allowed to stabilize at atmospheric pressure. During the filling operation, the helium pressurization system mounted on the scale platform is pressurized to approximately 1,800 psig in preparation for the test run. Upon completion of filling the 650-gallon calibration tank, the backflow of test fluid is discontinued. The vent valve on the 650-gallon calibration tank is closed and the tank pressure increased to approximately 50 psig using the scale pressurization system. The predetermined desired flow rate is then rapidly established and steady state flow conditions are attained within approximately 15 seconds. At this point, the scale system which has been previously balanced to equal the initial weight of the full storage vessel, minus a weight of predetermined liquid approaches the balanced condition of the scale. As the balance beam moves through its initial trig loop, the capacitance switch which senses beam movement is actuated initiating the following operations:

a. A synchronous clock is started furnishing a time base for the calibration run.

b. Specific instrumentation is activated to record both the instantaneous and totalized output of the flowmeter during the test period.

c. Calibrated weights are lowered onto the scale platform corresponding to the weight of fluid to be removed from the scale system during the calibration period.

The addition of the calibrated weights to the scale platform causes the scale to become unbalanced and the balance beam to return to its original position. As the flow of liquid from the calibration tank continues, the scale again approaches the balance condition. When balance is achieved, the balance beam again travels through its trig loop and actuates the capacitance switch stopping the standard timer and counters. The totalized output of the flowmeter being calibrated is then compared with the calibrated weight which was added to the scale system during the calibration period. It should again be noted that since the flowmeters undergoing calibration are mass flowmeters and the basic measurement on the scale system is a weight change, no additional information or instrumentation is required to determine the calibration factor of the meters being calibrated.

Determination of System Accuracy

Due to the lack of an accurate primary standard against which the calibration system may be compared, it is necessary to evaluate the system accuracy by means of an error analysis. The basic elements affecting the ultimate accuracy of the calibration system are attributed to the fundamental accuracy of the scale, extraneous loading, dynamic lag, repeatability of the capacitance switch and accuracy of the calibrated weights. The error analysis as presented in the following section is intended to arrive at an estimate of the accuracy for the time-weight calibration system. The analysis is based upon a maximum flow rate of 300 pounds per minute.

a) Scale Accuracy

The scale utilized is a special 8 x 4 foot platform-type scale capable of supporting a dead weight of 2,000 pounds. The scale system has been calibrated and is capable of measuring a weight change on the scale of 50 to 200 pounds to within a tolerance of one ounce or less. The sensibility reciprocal of the scale is less than one ounce. Due to the method of adding calibrated weights to the scale system to determine the weight change of fluid during the calibration period, the controlling characteristic of the scale is the sensibility reciprocal and scale repeatability rather than absolute accuracy of the scale. Based upon the sensibility reciprocal of less than one ounce and a test weight change of 100 pounds, the error contributed by the scale may be conservatively estimated as less than $\pm$ 0.0625%.

b) Extraneous Loading

The effects of extraneous loading on the accuracy of the calibration system are best analyzed by separating the external loading to vertical and horizontal components.

Vertical Loading:

Vertical loading of the scale is primarily a result of vertical forces transmitted through the flexible 3-inch withdrawal line and through several small instrumentation lines. Due to the technique of adding calibrated weights to the scale platform to simulate the weight change, the scale platform position will be identical for both the initial and final balance positions; thus, any vertical loading transmitted through flexible connections through the scale system should be compensating in nature resulting in an extremely low vertical loading. Due to the extreme difficulty in estimating actual vertical loading due to the flexible connections, tests will be conducted to establish the sensibility reciprocal of the scale under actual test conditions with all flexible connecting lines connected to the scale system. Preliminary tests have been conducted at ambient conditions with the flexible hoses unpressurized which indicate no apparent degradation of a sensibility reciprocal as a result of the flexible hose connections. For the present, and until such time as experimental data under actual conditions is obtained, a vertical loading component of $\pm$ 0.1% will be conservatively assumed for the present system accuracy analysis.

Horizontal Loading:

Horizontal loading tests have been conducted which indicate that horizontal loads up to 50 pounds do not result in a degradation of a sensibility reciprocal of a scale. Since the total side loading of the scale system is expected to be less than 50 pounds, the scale system accuracy will not be affected by horizontal loading.

c) Dynamic Lag and Capacitance Switch Repeatability

In estimating the effect of the scale's dynamic lag and repeatability of the capacitance switch, the following information is assumed:

1) Flow control during the test period is maintained within $\pm$ 2% of the desired flow rate between the initial and final balance points.

2) The actuation time of the scale system is predicted from the technique outlined in Reference 12.

$$T = \left[\frac{6HW}{KG} \right]^{1/3} \qquad (1)$$

where

T = actuation time of the scale system (sec)
H = distance traveled by the beam pointer before actuating the capacitance
W = system weight (lb)
K = flow rate (lbs/sec)
G = gravitational constant (ft/sec/sec)

3) The capacitance switch to be utilized in the scale system has been calibrated and found to be repeatable to within $\pm$ 0.0002 inch.

The errors introduced as a result of the scale dynamic lag and capacitance switch repeatability may be directly attributed to the failure to register the initial incremental weight during the first actuation and the over-registration of a second incremental weight during the final actuation. These gravimetric increments are shown graphically in Figure 18. The weights W_1 and W_2 may be found by applying the previously established information regarding flow control, actuation time and capacitance switch repeatability.

$$W_1 = (102\%) \ (K) \ (T_1) \qquad (2)$$

$$W_2 - (98\%) \ (K) \ (T_2) \qquad (3)$$

The total gravimetric error due to the dynamic lag and magnetic switch repeatability will then be

$$\Delta W = (102\%) \ (K) \ (T_1) - (98\%) \ (K) \ (T_2) \qquad (4)$$

where

$$T_1 = \left[\frac{6H_oW \ (1+\Delta H/H)}{GK_o \ (1+\Delta K/K)} \right]^{1/3} \qquad (5)$$

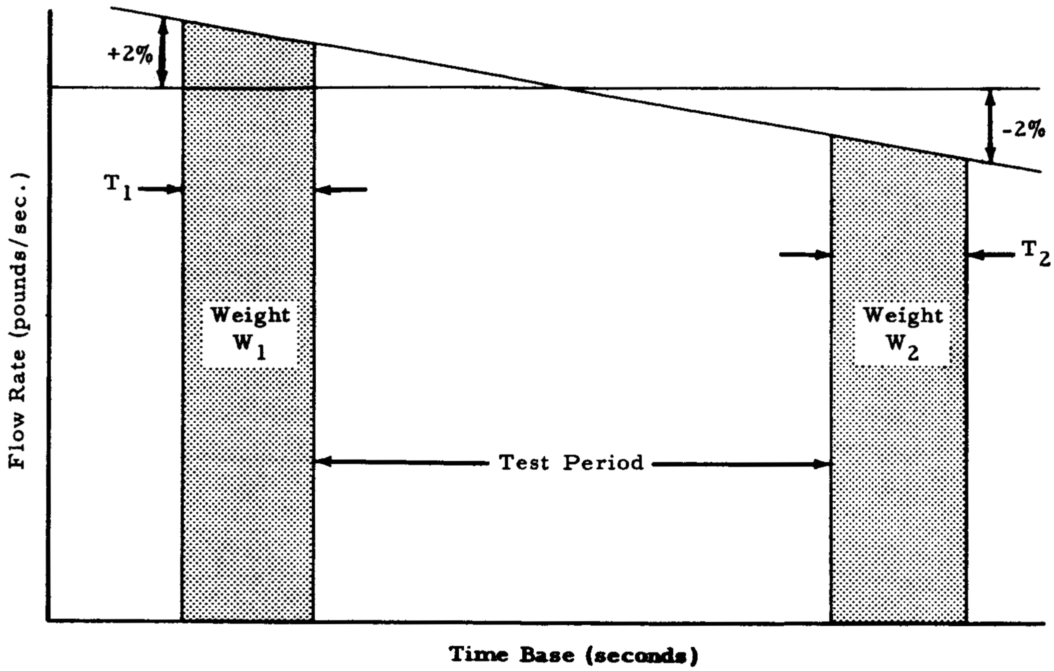

FIGURE 18

GRAPHICAL REPRESENTATIVE OF ERRORS
CREATED BY DYNAMIC LAG

and

$$T_2 = \left[\frac{6H_oW \ (1- \ H/H)}{GK_o \ (1- \ K/K)}\right]^{1/3} \qquad (6)$$

Evaluation of the system parameters yields

$$\Delta H/H = (0.0002)/(0.0012) = 16.7\%$$

$$\Delta K/K = 2\%$$

$$W = 2{,}000 \text{ pounds}$$

substitution of equations (5) and (6) into equation (4) yields

$$\Delta W = (0.022) \ (K_o)^{2/3} \qquad (7)$$

The error for a total weight change of 100 pounds is

$$\text{Percent Error} = 2.2 \times 10^{-4} \ (K_o)^{2/3} \qquad (8)$$

It is seen that the error due to the dynamic lag of the scale and capacitance switch repeatability increases with flow rate.

d) Specific Volume of Test Media

In order to determine the volumetric flow rate (in the calibration of volume flowmeters only) which has been displaced through the flowmeter from the total weight change experienced by the scale, it is necessary to accurately determine the specific volume of the test fluid media for conditions existing in the test section. Fluid temperature has a relatively large effect on the determination of the specific volume of a cryogenic fluid, e.g., in the case of liquid hydrogen an error in temperature measurement of ± 0.5°F will introduce an error in the specific volume determination of approximately ± 0.6%.

e) Calibrated Weights

The standard weights shown in Figure 6 have been calibrated to within an accuracy of ± 6 grains by the Riverside County Bureau of Weights and Measures. The resultant error for each individual 50-pound weight is ± 0.002%.

f) Total System Accuracy

By totalizing the error attributed by each individual source, the total system accuracy may be estimated for a maximum flow rate of 300 pounds per minute as shown in the table below. System accuracies are estimated for the calibration of both mass and volume-type flowmeters.

	Error	$(\text{Error})^2$
Scale	0.0625	0.0039
Extraneous Loading	0.1	0.01
Dynamic Lag and Capacitance Switch	0.0645	0.0045
Specific Volume	0.6*	0.36*
Calibrated Weight	Negligible	0
*Volume Meter	0.8270%	0.3781
Mass Meter	0.02270%	0.0181

*For calibration of volume meters only.

From the above table, it is seen that the maximum expected error for the calibration of mass flowmeters is ± 0.23%, while for the calibration of volume flowmeters the maximum expected error is ± 0.83%. A more realistic evaluation of the expected system error is obtained from the RMS error of ± 0.13% and ± 0.61% for the calibration of mass flowmeters and volume flowmeters, respectively.

EXPERIMENTAL PROGRAM

The Potter and Decker mass flowmeters shall be subjected to the following Experimental Program:

Preliminary Evaluation Tests with Liquid Nitrogen

Preliminary tests shall be performed using liquid nitrogen as the test medium. These preliminary tests shall consist of five point calibrations of each meter. One calibration point shall be obtained at 150 pounds per minute and two calibration points shall each be obtained at 225 and 300 pounds per minute of liquid nitrogen. The purpose of the preliminary tests may be briefly summarized as follows:

1) To provide data which will enable a comparison of the flowmeter performance between ambient temperature, using water as the test medium, and cryogenic conditions using liquid nitrogen as the test medium.

2) Investigate potential degradation of the flowmeter performance as a result of use in cryogenic conditions.

3) Evaluate and substantiate the over-all performance of the calibration test stand.

4) Investigate possible correlation functions relating to the performance of the flowmeter at ambient conditions with the flowmeter performance at cryogenic conditions.

Calibration with Liquid Hydrogen

Following the completion of the preliminary evaluation tests with liquid nitrogen, the flowmeters shall be subjected to a detailed calibration, using liquid hydrogen as the test medium. Calibration points shall be obtained at the following flow rates:

One calibration point at 30, 75 and 150 lbs/min.

Two calibration points at 180 and 300 lbs/min.

Three calibration points at 210, 240 and 270 lbs/min.

The purpose of the calibration tests with liquid hydrogen is to establish the flowmeter performance with liquid hydrogen. Performance parameters such as accuracy, repeatability, linearity and pressure drop, shall be evaluated.

Variable Density Test with Liquid Hydrogen

Following the successful completion of the liquid hydrogen calibration, the flowmeters shall be subjected to single point calibrations, with varying degrees of density variation. The purpose of this test is to evaluate the capability of the flowmeters to function and accurately meter liquid hydrogen under both single and two phase flow conditions, with varying degrees of density variation.

Each meter shall be subjected to a ten point calibration at a flow rate to be determined from the previous liquid hydrogen calibration data. The first five points of the variable density test shall be performed by injecting increasing quantities of helium into the flow system and monitoring the resultant meter performance. In this manner, quantitative data relating the meter performance as a function of two phase flow conditions may be developed. The remaining five points of the Variable Density Test shall be performed by allowing the liquid hydrogen in the 650-gallon calibration tank to absorb heat and, thus achieve varying degrees of sub-cooling prior to the initiation of the test run. By monitoring the condition of test fluid entering the meter and the subsequent meter performance, a qualitative insight into the meter performance under single and two phase conditions will be obtained.

Evaluation of Additional Meters

In the event that additional meters are added to the experimental program at a later date, the experimental program will consist of either the program outlined above, or some combination thereof, or may be altered as a result of evaluation of the test data obtained during evaluation of the Potter and Decker flowmeters.

ANALYSIS AND DESIGN IMPROVEMENTS OF FLOWMETER DESIGN

Provisions have been included in the program scope for the analysis and design improvement of the Potter and Decker mass flowmeters. It is intended that the effort expended in this portion of the program be utilized in an optimum manner based upon the experimental phases of the program. Design modifications which may be evident as a result of the experimental program will be fully coordinated with the flowmeter manufacturer prior to performing modifications upon the test unit flowmeter. All phases of analysis and design improvement will be within the over-all program scope for the analysis and design improvement phase of the program.

At the present time, provisions have not been included in the program scope for possible analysis and design improvement of additional flowmeters which may be added to the program at a later date.

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